Performance of FRP Strengthened Concrete Beams Anchored with Fiber Anchors Under Cyclic Loading

Kansas State University

Department of Civil Engineering

Salman Alshamrani

Ph.D. Student

Prof. Hayder Rasheed

Major Advisor

Fahed Salahat

Stand Structural Engineering Inc.

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Outline

1. Introduction

- One of the main applications of FRP strengthening is to improve the flexural capacity of reinforced concrete (RC) beams by bonding FRP composites to the soffit.
- Over the last several years, CFRP anchors have received research attention as anchorage devices that can mechanically transfer forces from the FRP sheet into the concrete substrate.

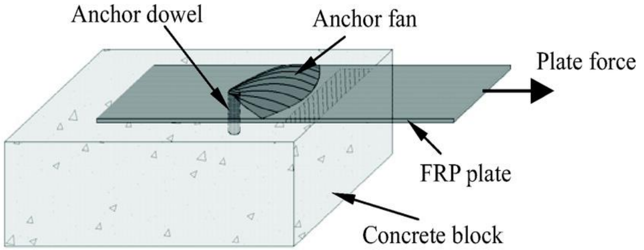
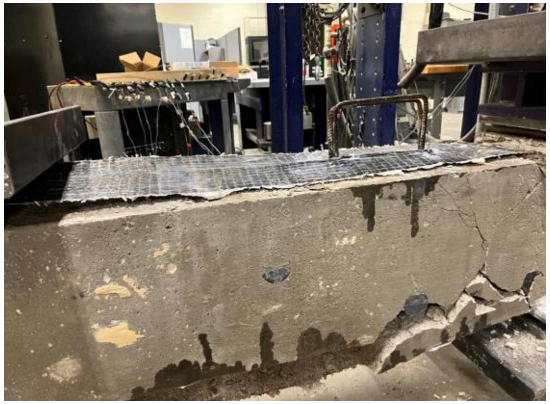


Figure: CFRP splay anchors

2. Research Objectives

- Investigate the effectiveness of using carbon fiber anchors to secure CFRP sheets in the full-scale RC beams subjected to reversed cyclic loading.
- Examine the contribution of anchors in changing the failure mode from debonding of the CFRP sheet to CFRP rupture.



← Debonding

Rupture →

Figure: CFRP sheet debonding and rupture

3. Specimen Description

Control Beam No.1:

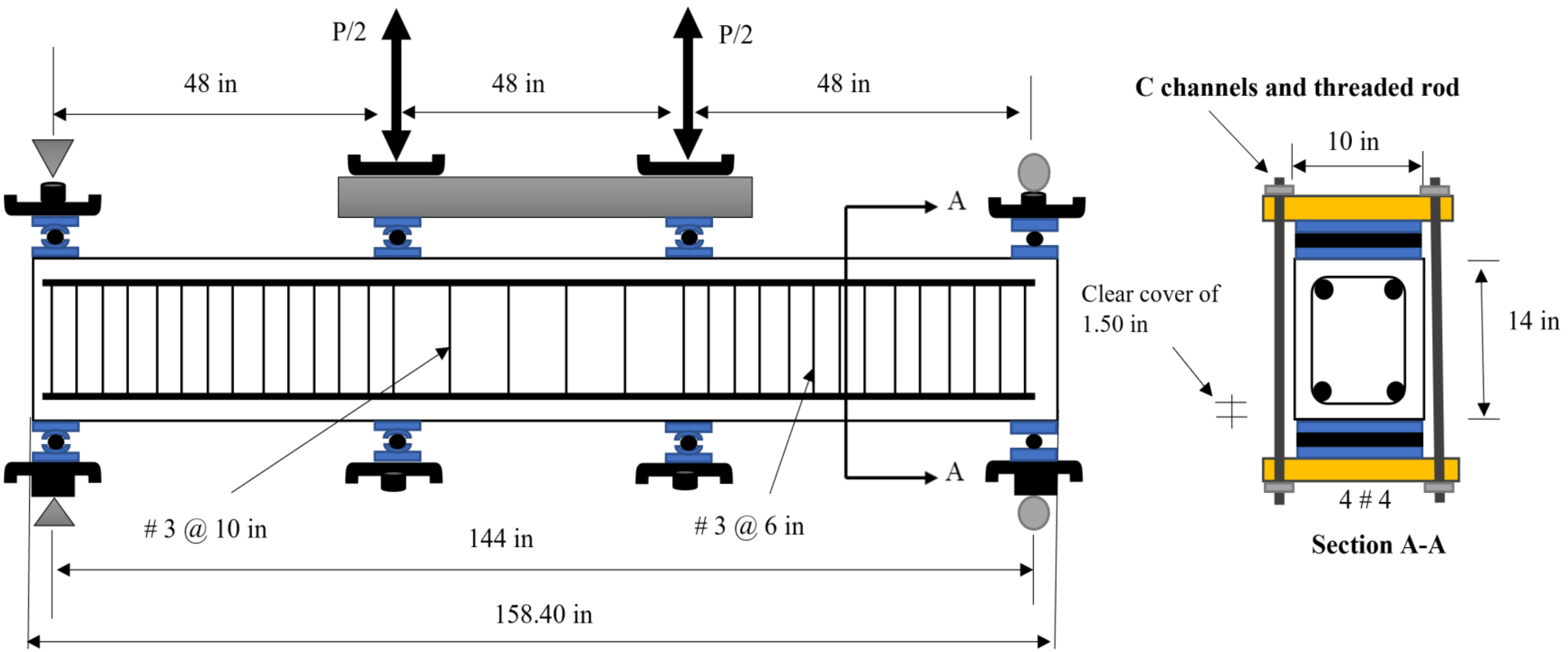


Figure: Beam No.1 cross section details

3. Specimen Description Cont.

Beam No.2:

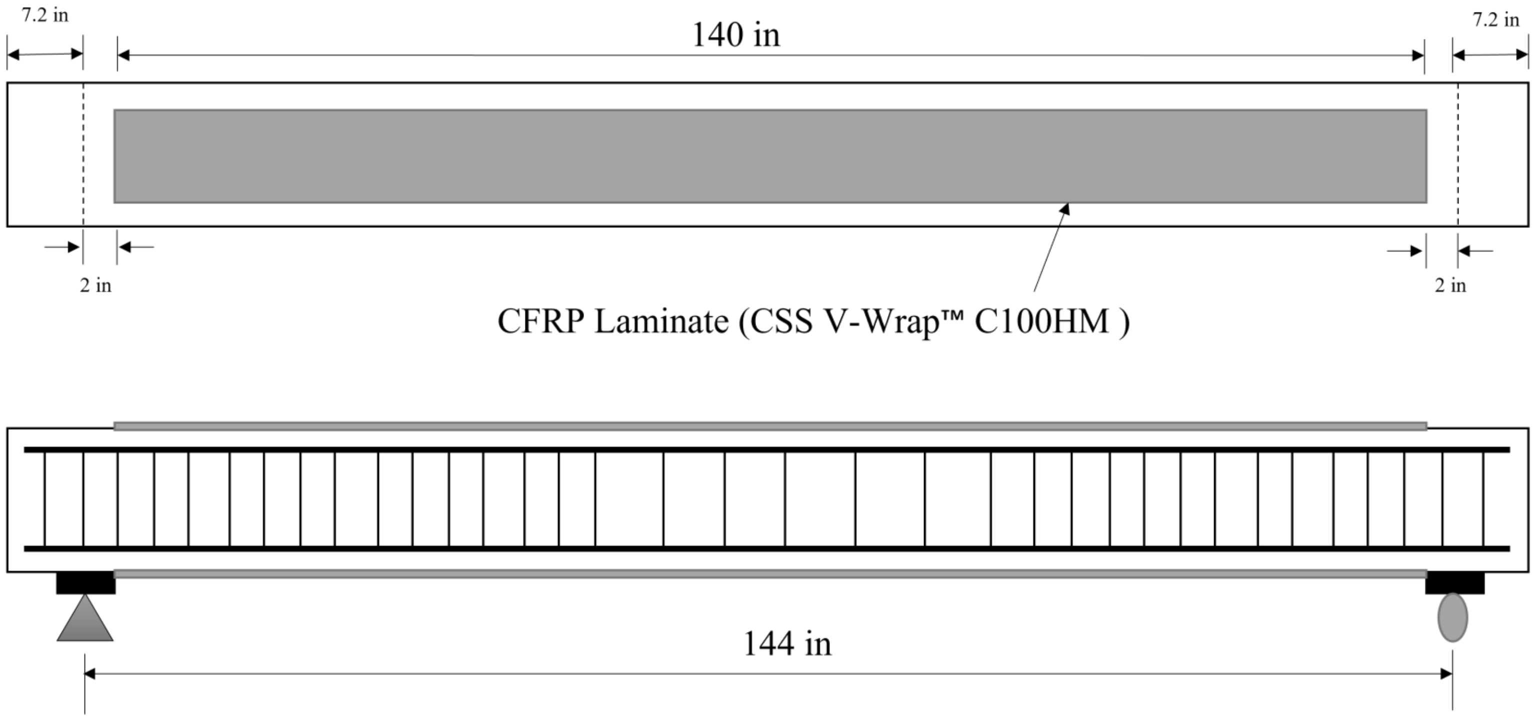


Figure: Beam No.2 cross section details

3. Specimen Description Cont.

Beam No.3:

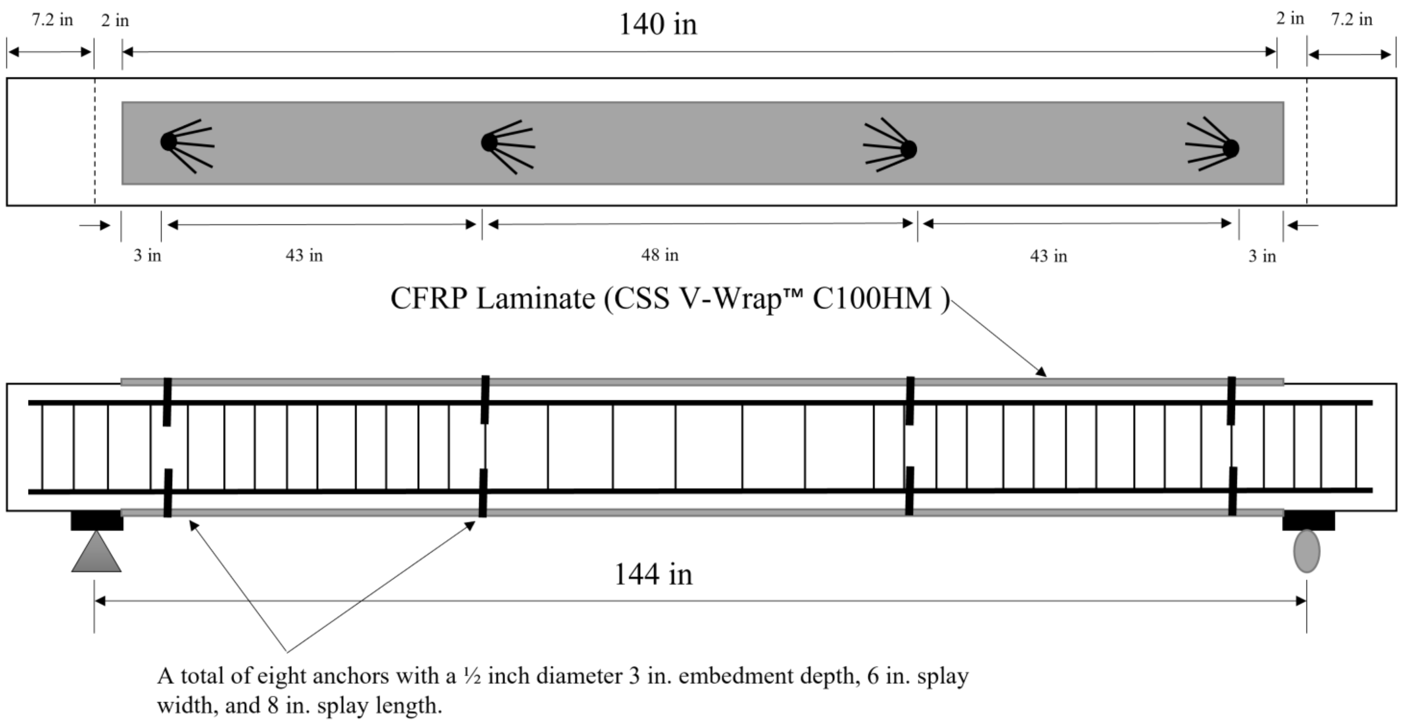


Figure: Beam No.3 cross section details

3. Specimen Description Cont.

Beam No.4:

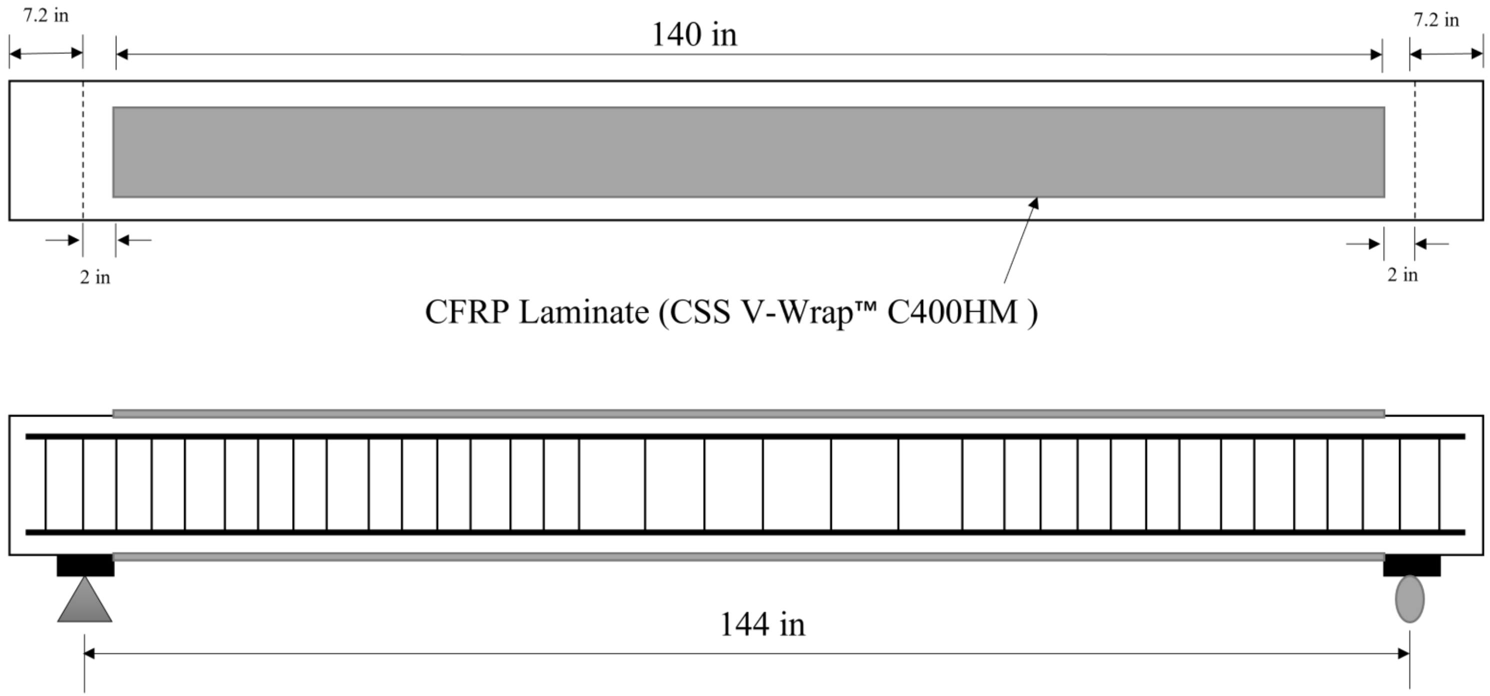


Figure: Beam No.4 cross section details

3. Specimen Description Cont.

Beam No.5:

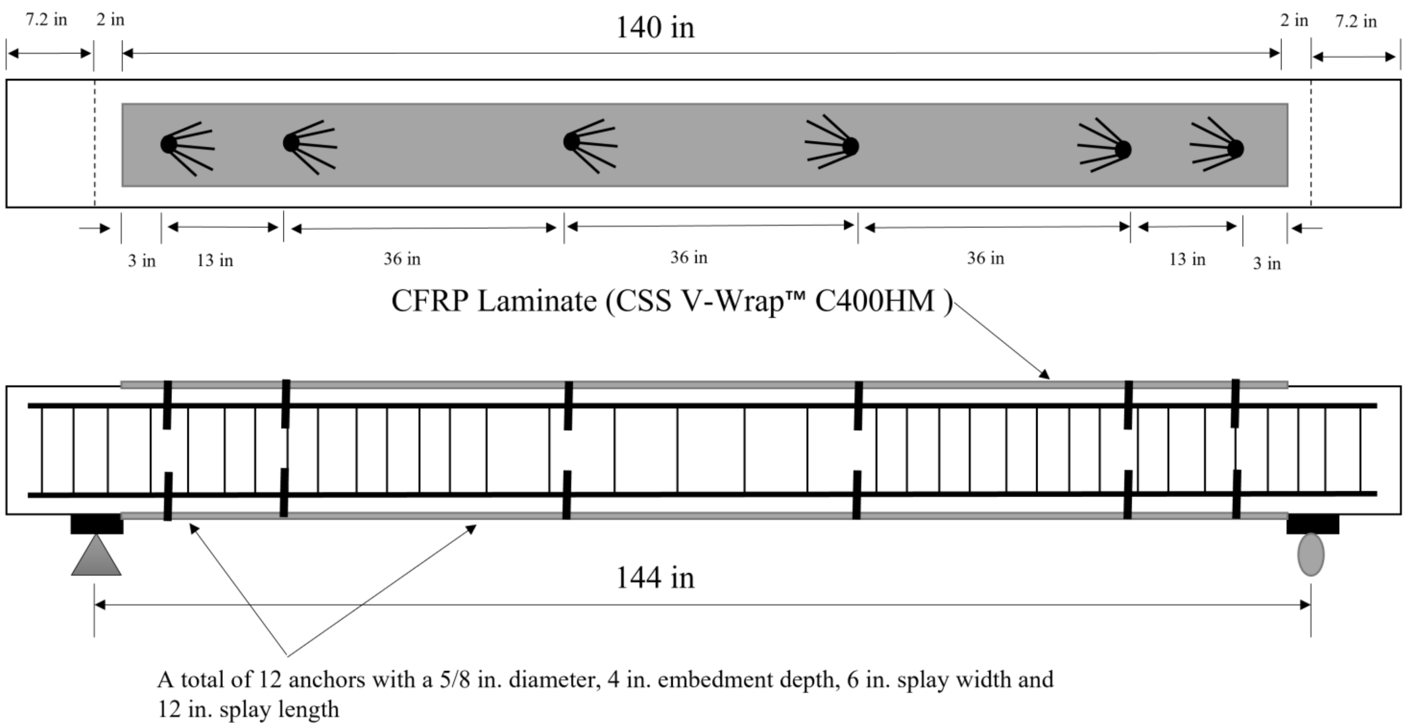


Figure: Beam No.5 cross section details

4. Materials Properties

- ## Concrete and Steel Properties

Material	Compressive Strength (psi)	Yield Strength (Ksi)	Modulus of Elasticity (Ksi)
Concrete (Designed value)	2,500		2,850
Concrete (Experimental value)	3,049		3,739
Steel No.3 (Manufactured value)		68.20	29,000
Steel No.3 (Experimental value)		70.40	25,118
Steel No.4 (Manufactured value)		83.10	29,000
Steel No.4 (Experimental value)		77.74	24,727

4. Materials Properties

- **FRP Properties**

<u>CSS V-Wrap™ C100HM</u>

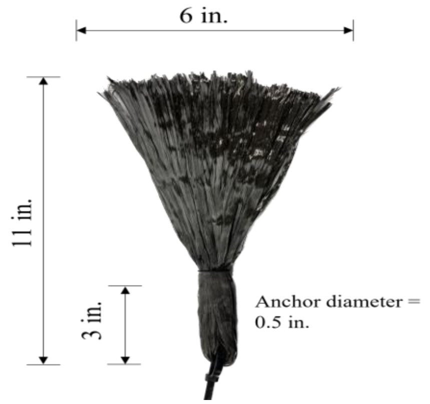
$f_{fu} = 180\ ksi$
$E_{fu} = 16700\ ksi$
$\varepsilon_{fu} = 0.0130$
$t_f = 0.02\ in.$

<u>CSS V-Wrap™ C400HM</u>

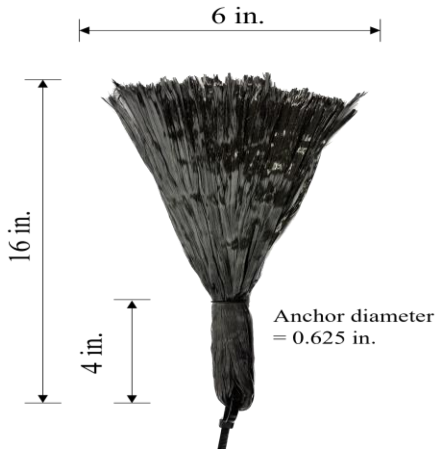
$f_{fu} = 180\ ksi$
$E_{fu} = 14240\ ksi$
$\varepsilon_{fu} = 0.0127$
$t_f = 0.08\ in.$

4. Materials Properties

- **FRP Properties: HM CFRP Anchors**

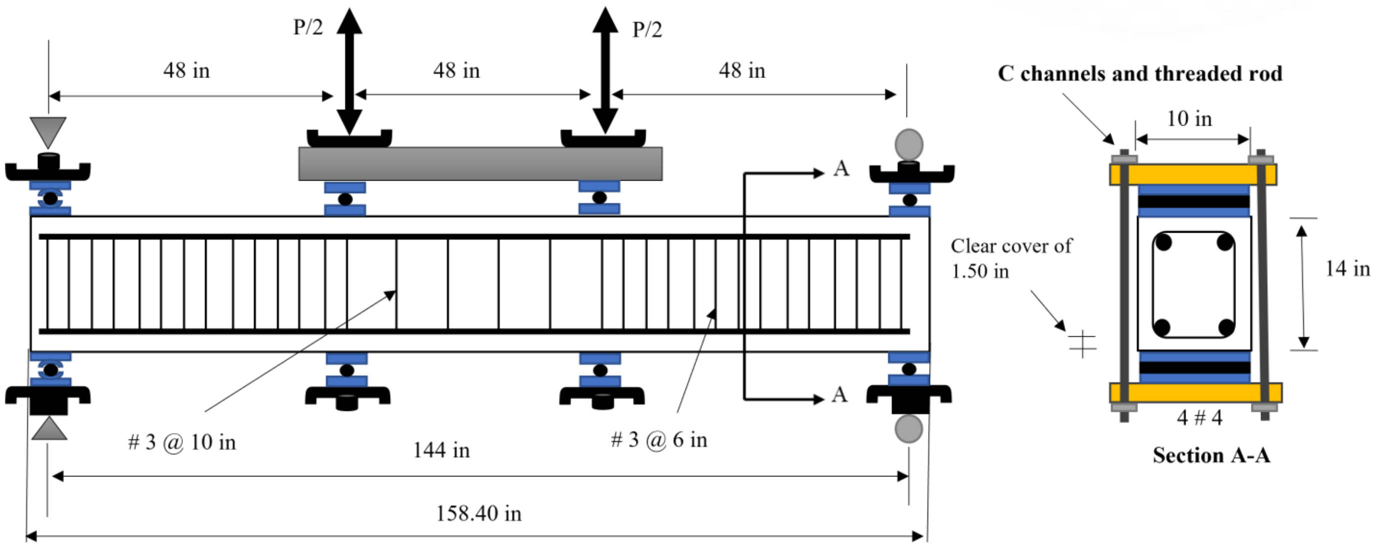


$T_f = 165\ ksi$
$E_f = 15000\ ksi$
$\varepsilon_{fu} = 0.011$
Anchor diameter = 0.5 in.
Design area = 0.196 in.^{2}
Used with thin CFRP sheets



$T_f = 165\ ksi$
$E_f = 15000\ ksi$
$\varepsilon_{fu} = 0.011$
Anchor diameter = 0.625 in.
Design area = 0.306 in.^{2}
Used with thick CFRP sheets

5. Lab Test Setup



6. Experimental Program

- **Strengthening categories**

Beam No.	Specimen Type	CFRP Sheets	Number of layers
1	Control	N/A	N/A
2	FRP strengthened	CSS V-Wrap™ C100HM	1 top and bottom
3	FRP strengthened & anchored	CSS V-Wrap™ C100HM	1 top and bottom
4	FRP strenghened	CSS V-Wrap™ C400HM	1 top and bottom
5	FRP strengthened & anchored	CSS V-Wrap™ C400HM	1 top and bottom

6. Experimental Program

- **Specimens fabrication**

6. Experimental Program

- **Surface grinding to prepare for FRP installation**

6. Experimental Program

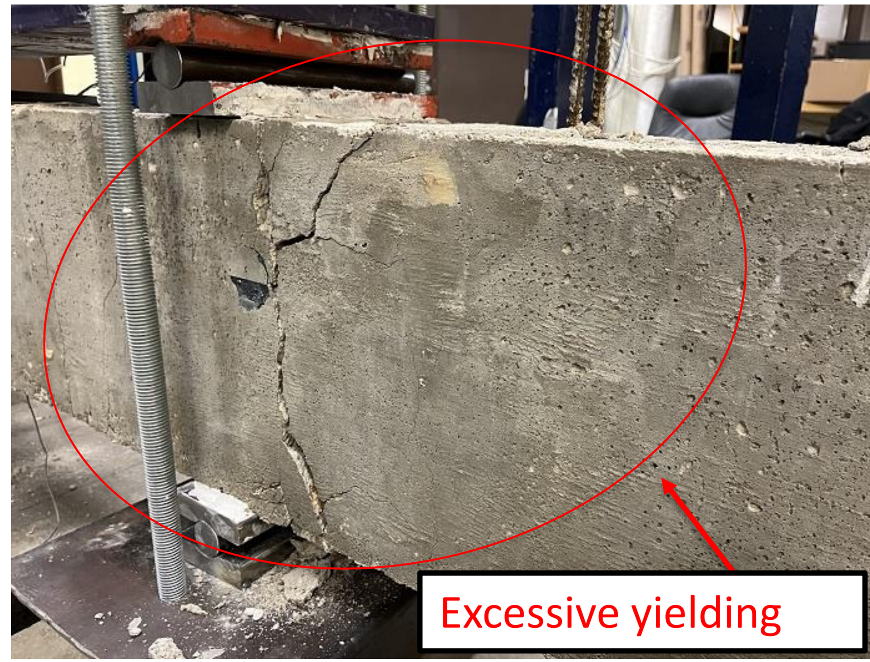
- **FRP installation**

7. Testing and Results

- **Testing**

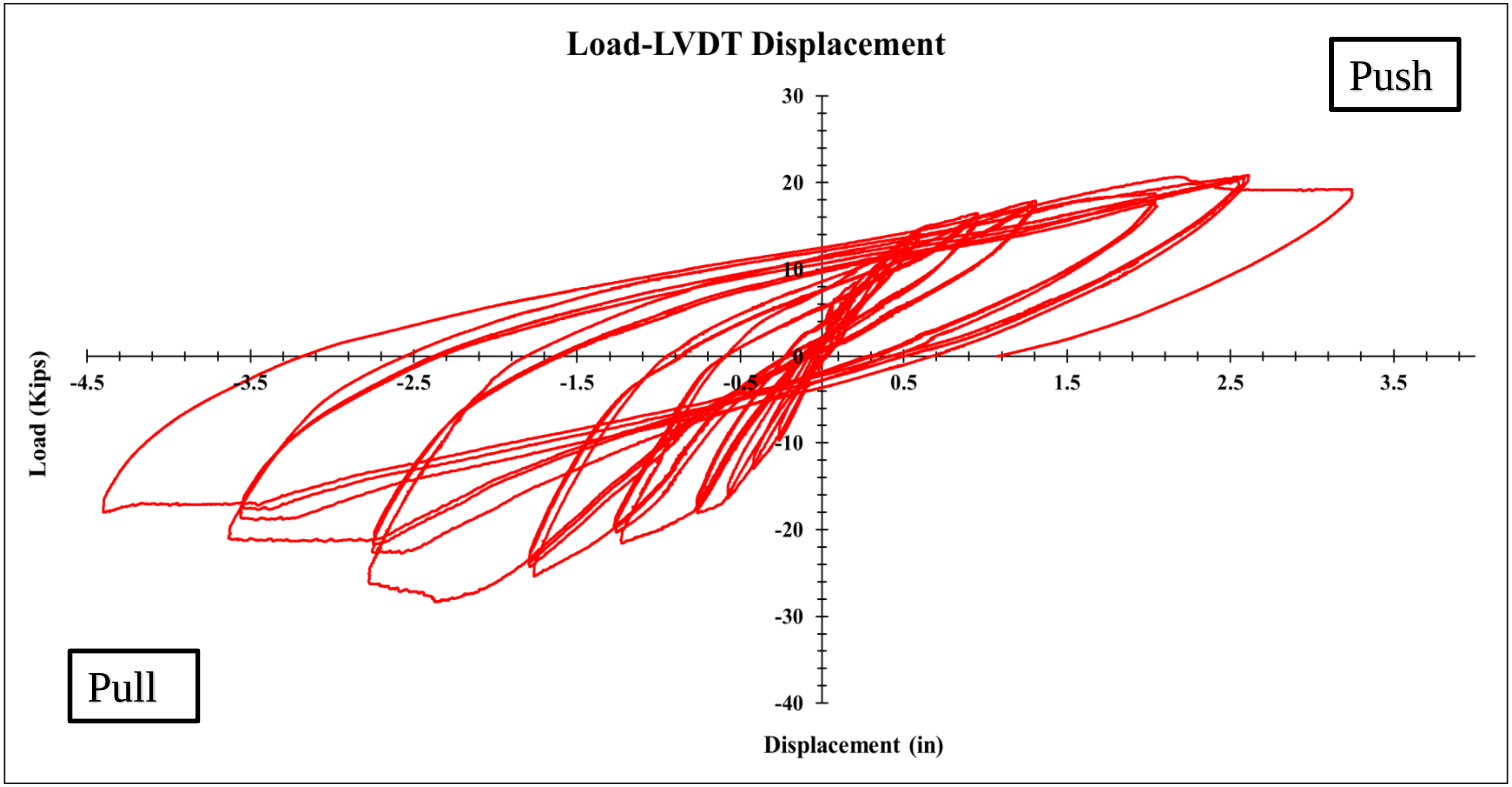
Beam No.1

- **Before and after testing**



Beam No.1

- Cyclic Response



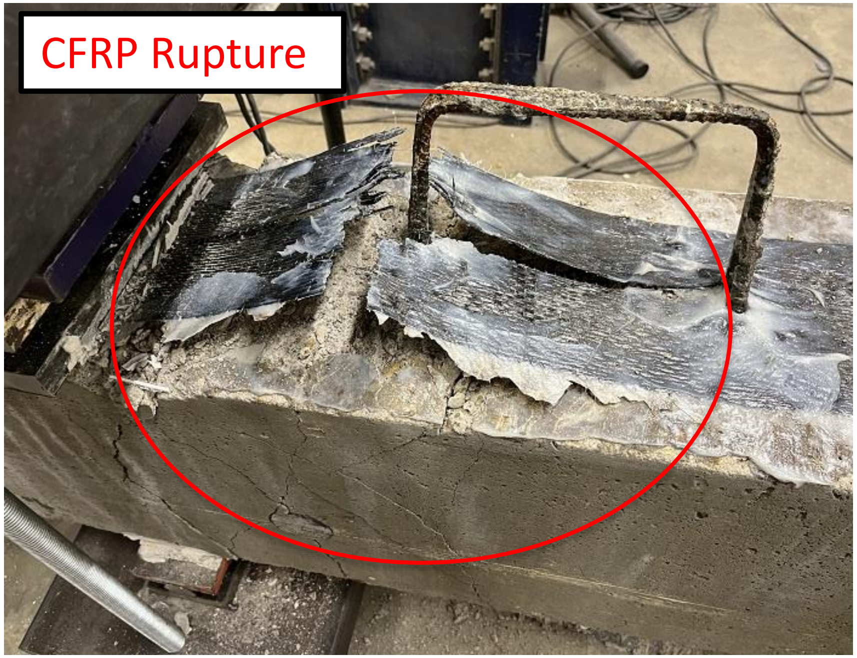
Beam No.1

- **Results summary**

- ❑ Failure Cycle (in): 3.6
- ❑ Yielding Cycle (in): 0.72
- ❑ μ : 5
- ❑ Maximum Load in Push (Kips): 20.85
- ❑ Maximum Load in Pull (Kips): 28.32
- ❑ Failure Mode : Excessive yielding

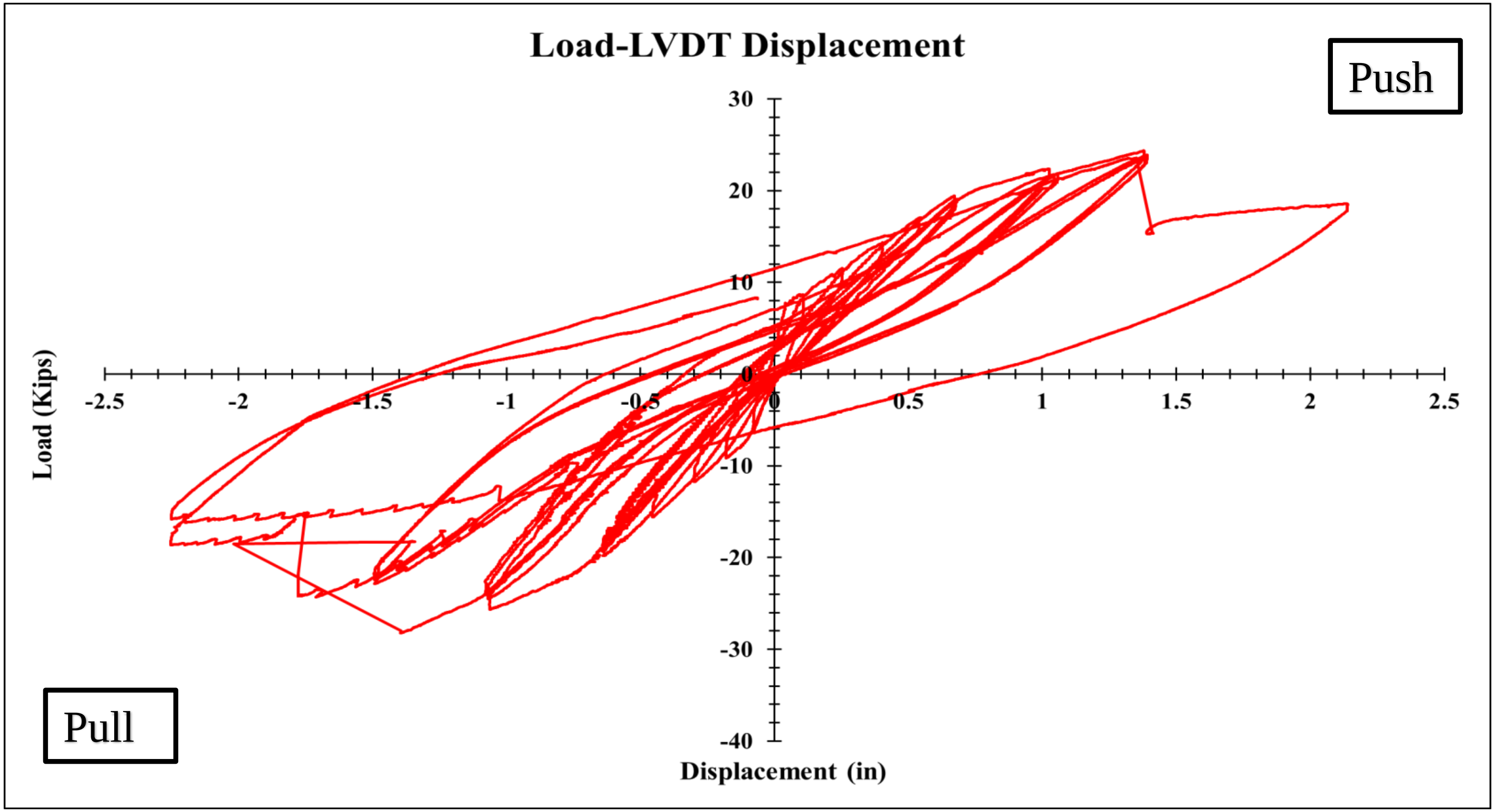
Beam No.2

- **Before and after testing**



Beam No.2

- Cyclic Response



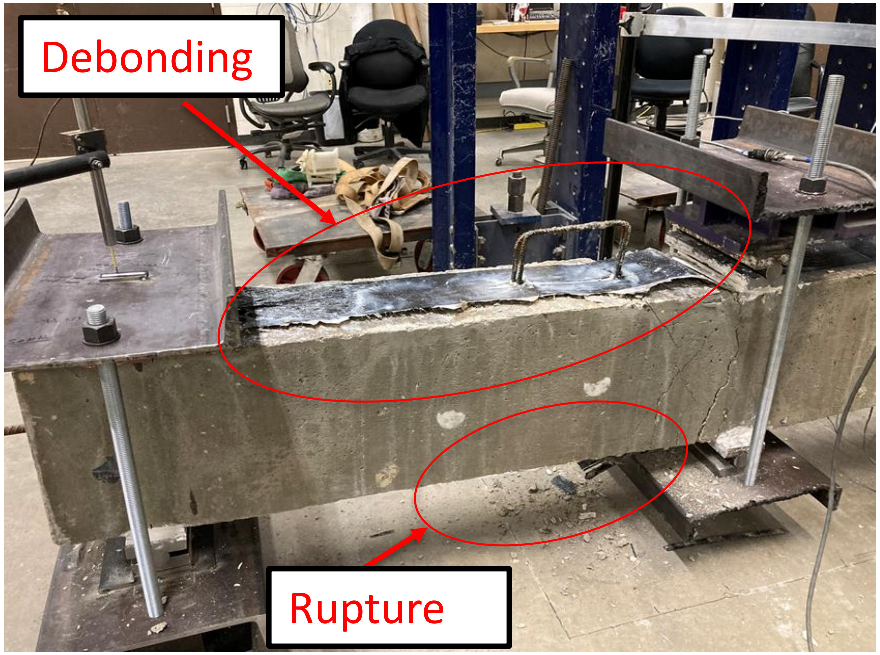
Beam No.2

- **Results summary**

- Failure Cycle (in): 2.25
- Yielding Cycle (in): 0.75
- μ : 3
- Maximum Load in Push (Kips): 24.33
- Maximum Load in Pull (Kips): 28.21
- Failure Mode : CFRP Rupture (shear span)

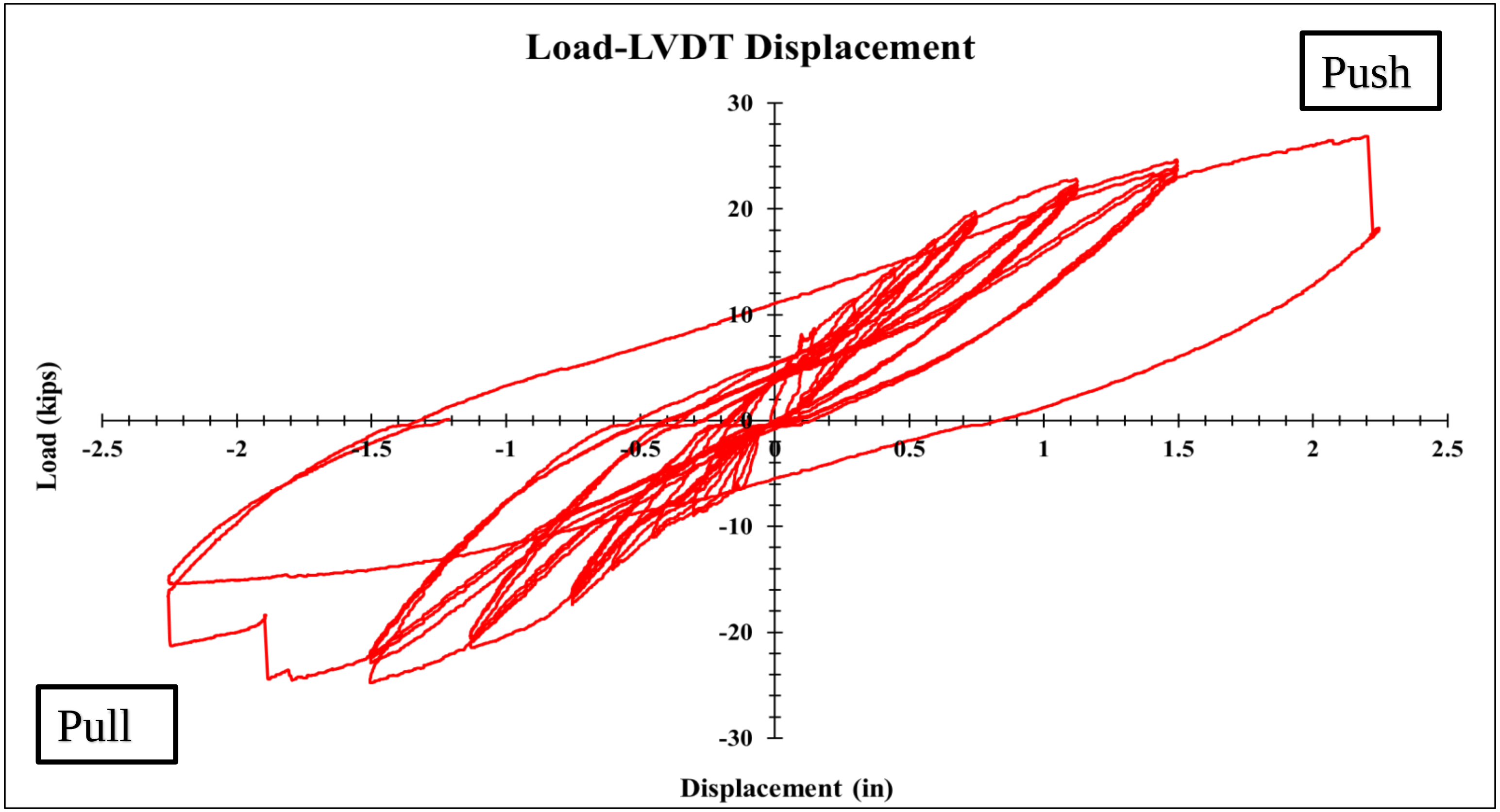
Beam No.3

- **Before and after testing**



Beam No.3

- **Cyclic Response**



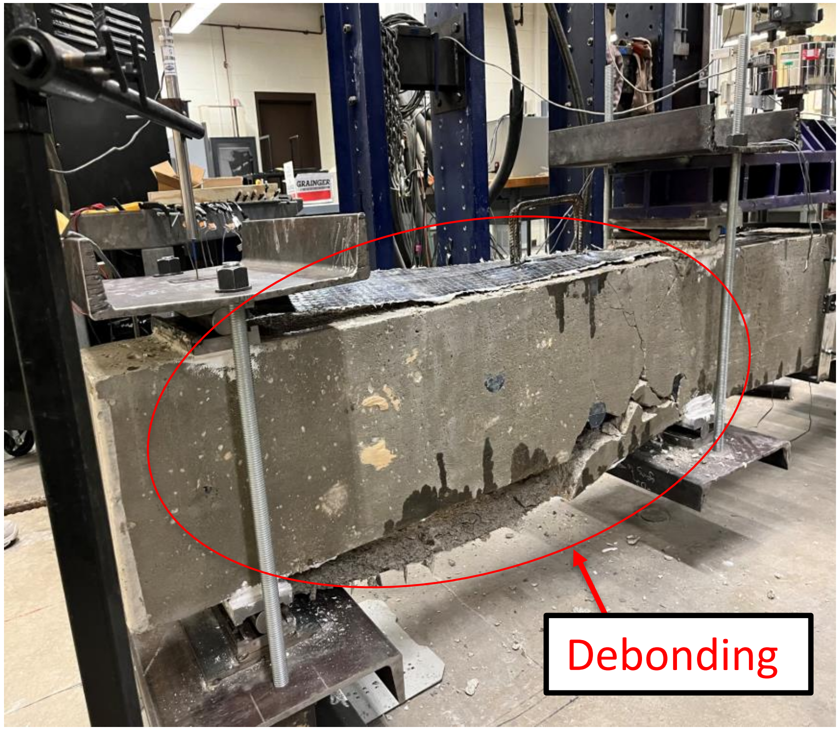
Beam No.3

- **Results summary**

- Failure Cycle (in): 2.25
- Yielding Cycle (in): 0.75
- μ : 3
- Maximum Load in Push (Kips): 26.87
- Maximum Load in Pull (Kips): 24.77
- Failure Mode : CFRP Debonding (shear span-Top) and CFRP Rupture (shear span-Bot)

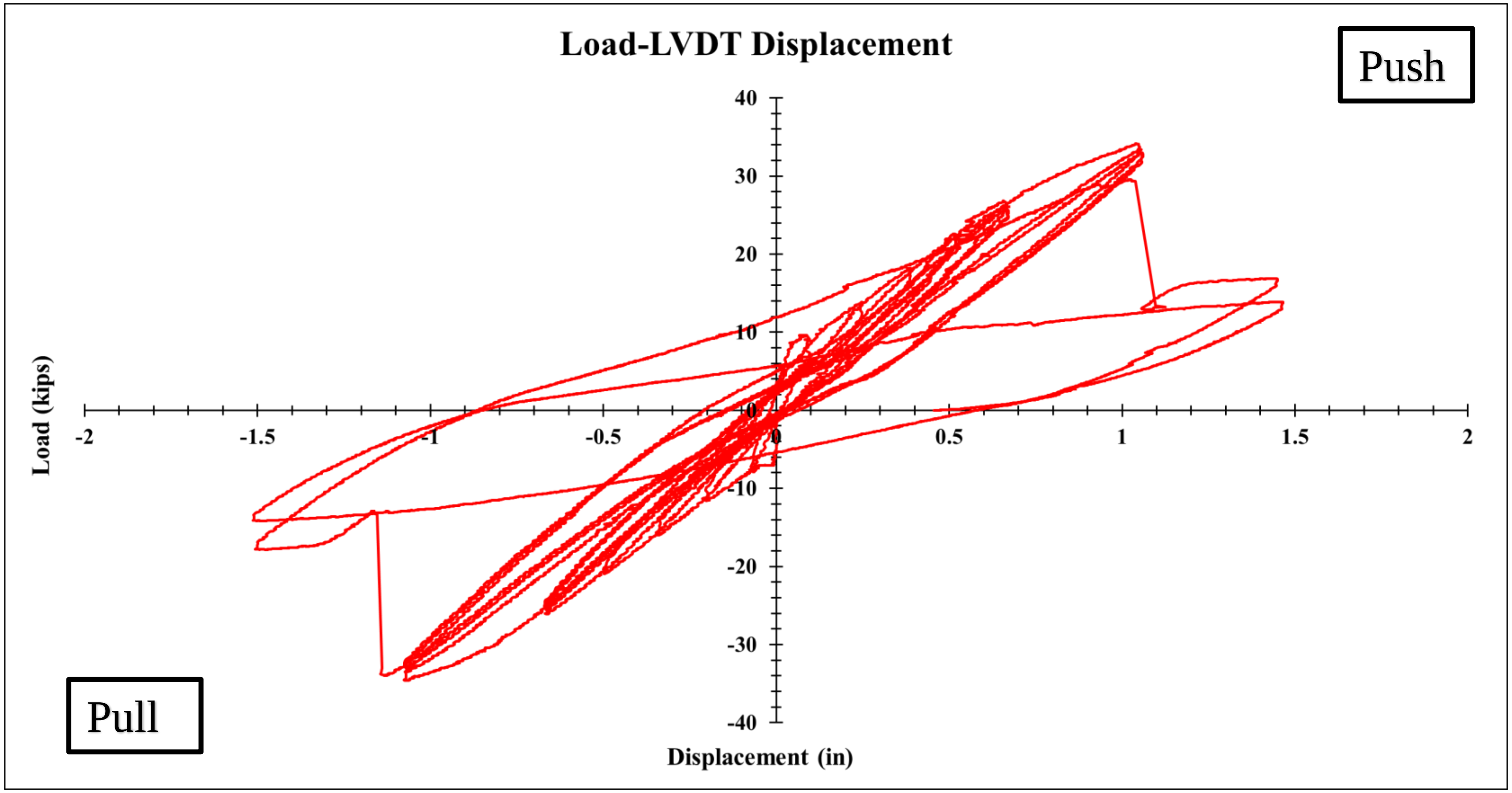
Beam No.4

- **Before and after testing**



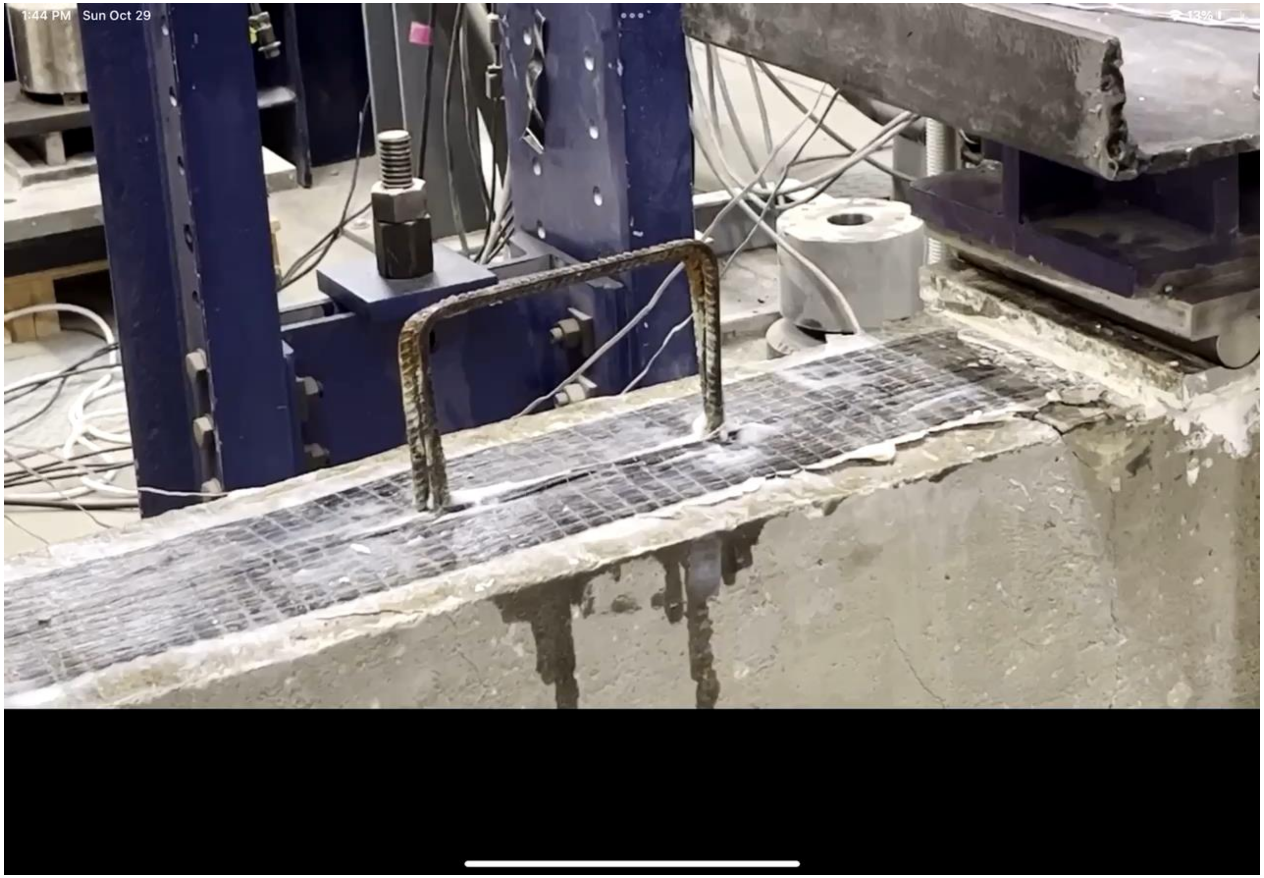
Beam No.4

- Cyclic Response



Beam No.4

- **Failure**



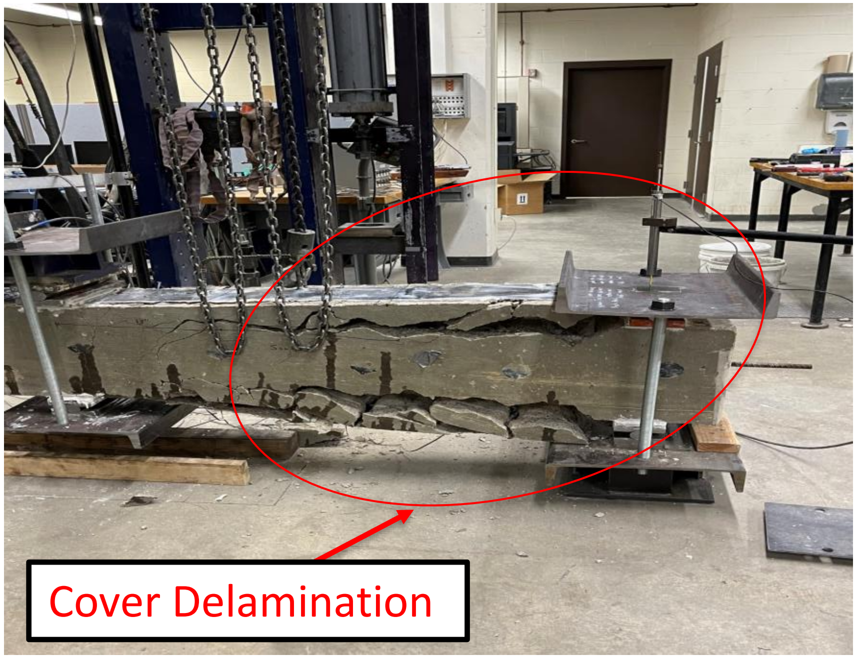
Beam No.4

- **Results summary**

- Failure Cycle (in): 1.6
- Yielding Cycle (in): 0.8
- μ : 2
- Maximum Load in Push (Kips): 34.63
- Maximum Load in Pull (Kips): 34.13
- Failure Mode : CFRP Debonding (shear span)

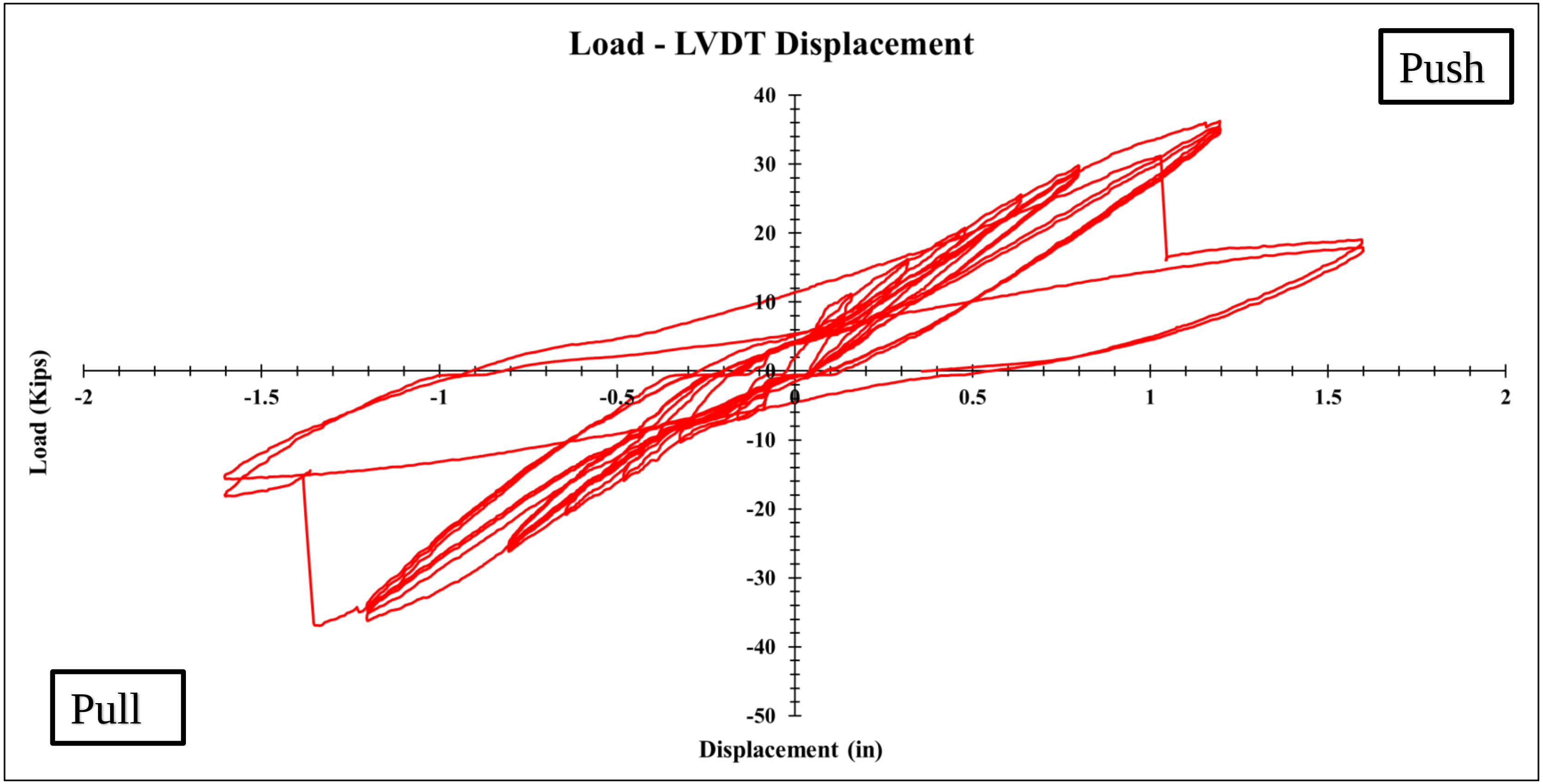
Beam No.5

- **Before and after testing**



Beam No.5

- **Cyclic Response**

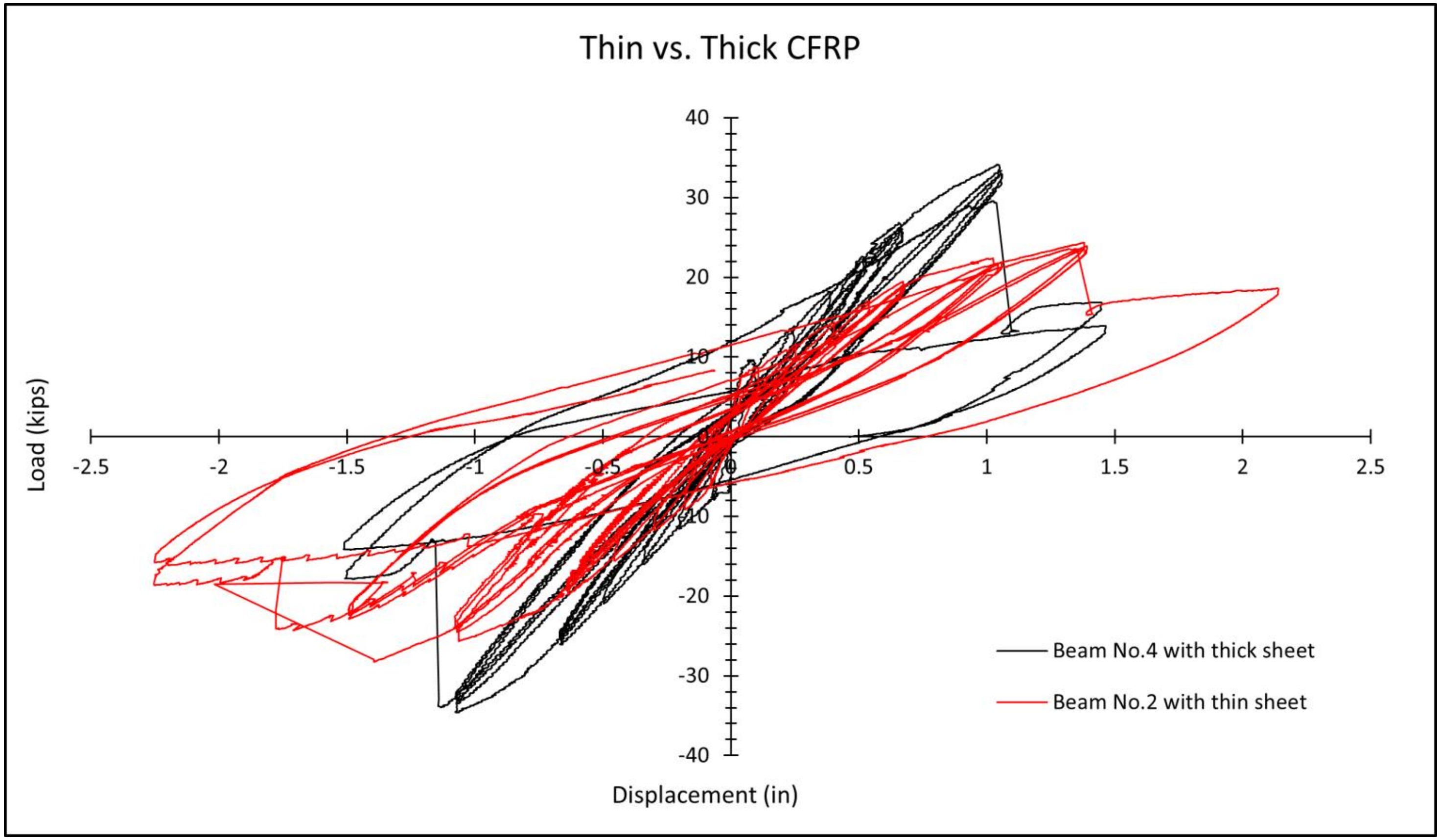


Beam No.5

- Results summary

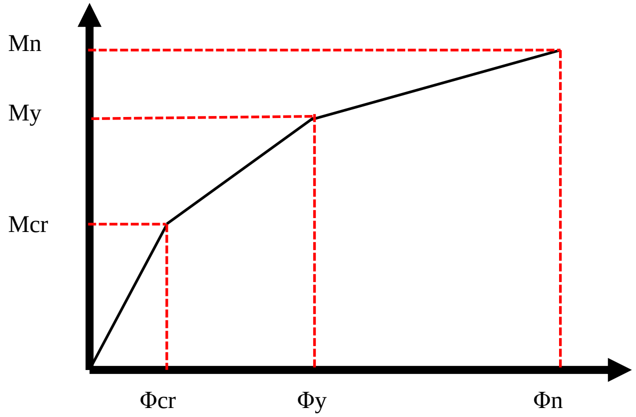
- ❑ Failure Cycle (in): 1.6
- ❑ Yielding Cycle (in): 0.8
- ❑ μ : 2
- ❑ Maximum Load in Push (Kips): 36.91
- ❑ Maximum Load in Pull (Kips): 36.25
- ❑ Failure Mode : Cover Delamination (shear span)

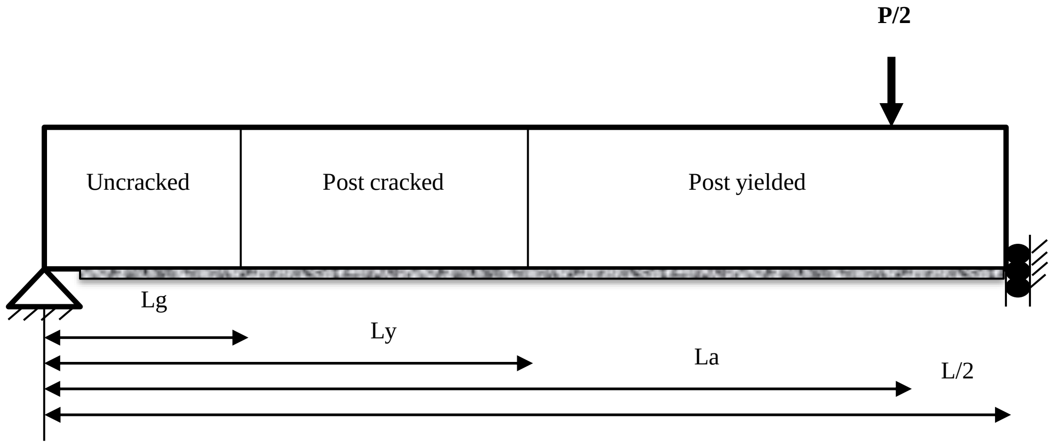
Thin vs. Thick CFRP Sheets



8. Analytical Model of Envelope Curve

- The trilinear approach developed by (Charkas et al. 2003) was used to predict the envelope curve response of the tested specimens.





Analytical Model of Envelope Curve Cont.

Displacement Four points bending:

$$\delta 1 = \left(\frac{\phi}{24}\right) * (3 * L2 - 4 * La2)$$

$$\delta 2 = \left(\frac{Ly}{6}\right) * \big(\phi cr * (Ly + La) - \phi * (Ly + La)\big)$$

$$\delta 3 = (\phi y * (La - Lg) * (La + Ly + Lg))/6))$$

$\boldsymbol{Total\ Displacement}$:

$if\ (Ma < Mcr):$

$$\delta\ total = \left(\frac{\phi}{24}\right) * (3 * L2 - 4 * La2)$$

$else\ if\ (Mcr < Ma < My)$

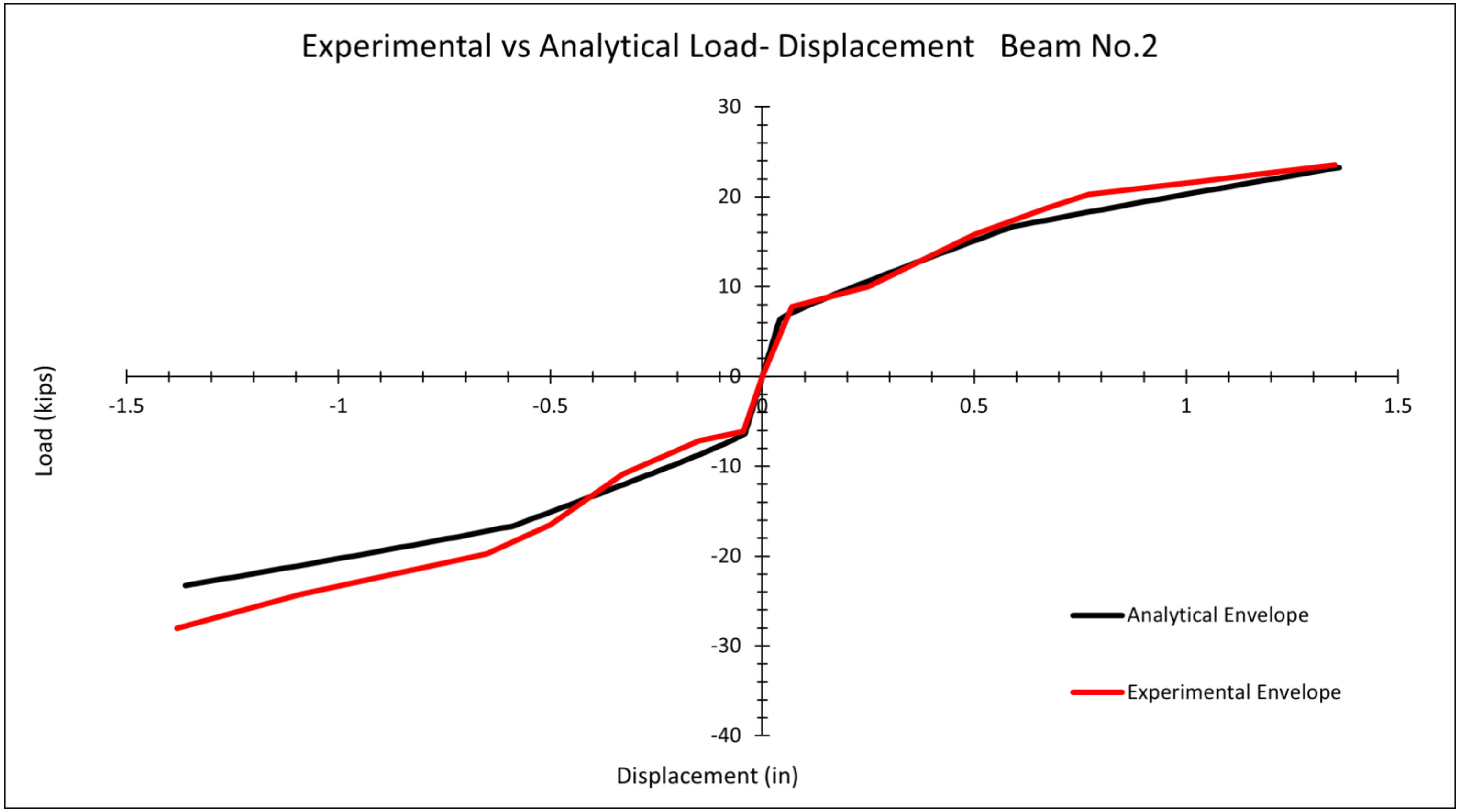
$$\delta\ total = \left(\frac{\phi}{24}\right) * (3 * L2 - 4 * La2) + \left(\frac{Lg+La}{6}\right) * (\phi cr * La - \phi * Lg)$$

else

$$\delta\ total = \delta 1 + \delta 2 + \delta 3$$

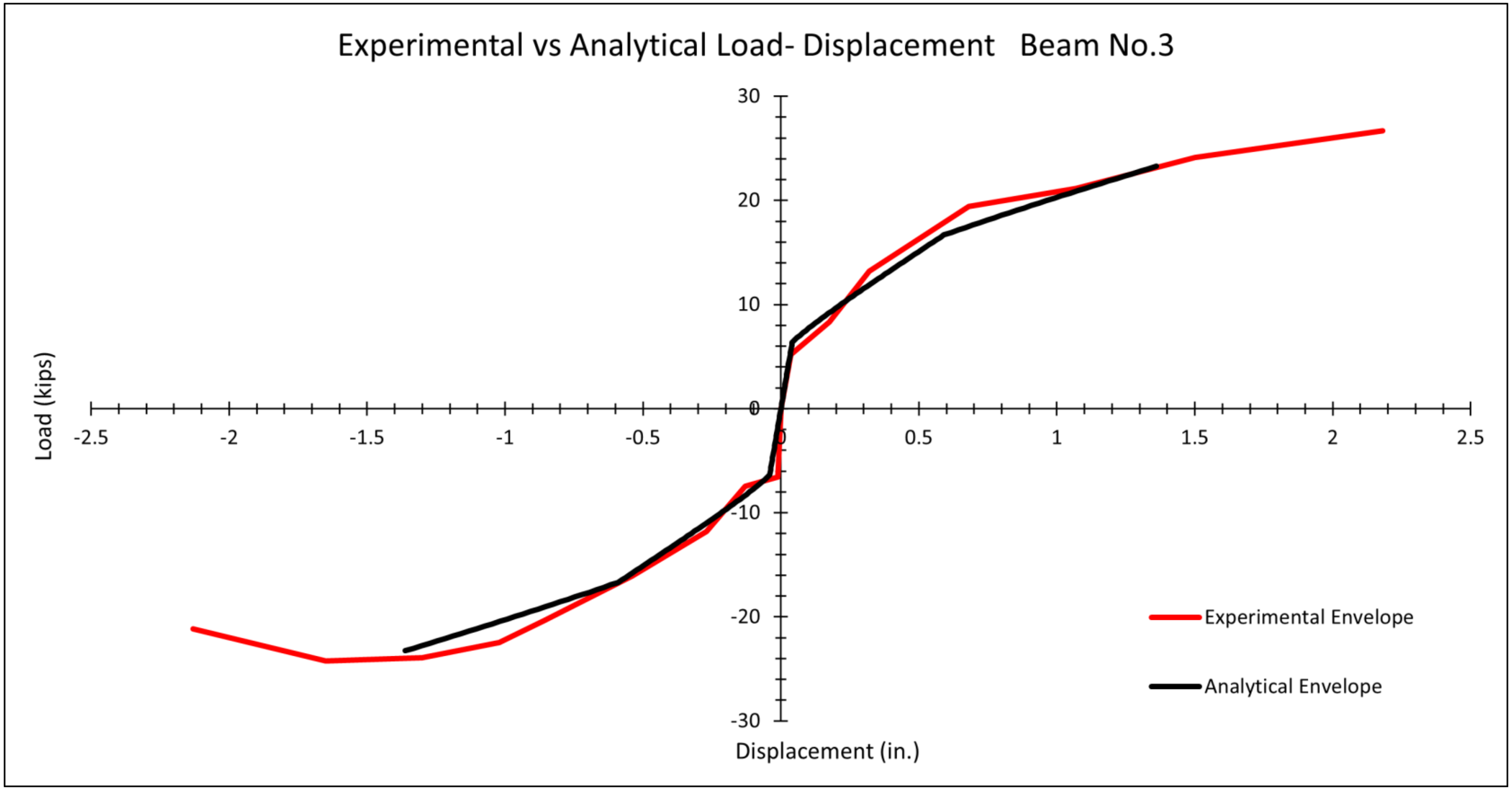
Analytical Model of Envelope Curve Cont.

❑ Experimental vs analytical model



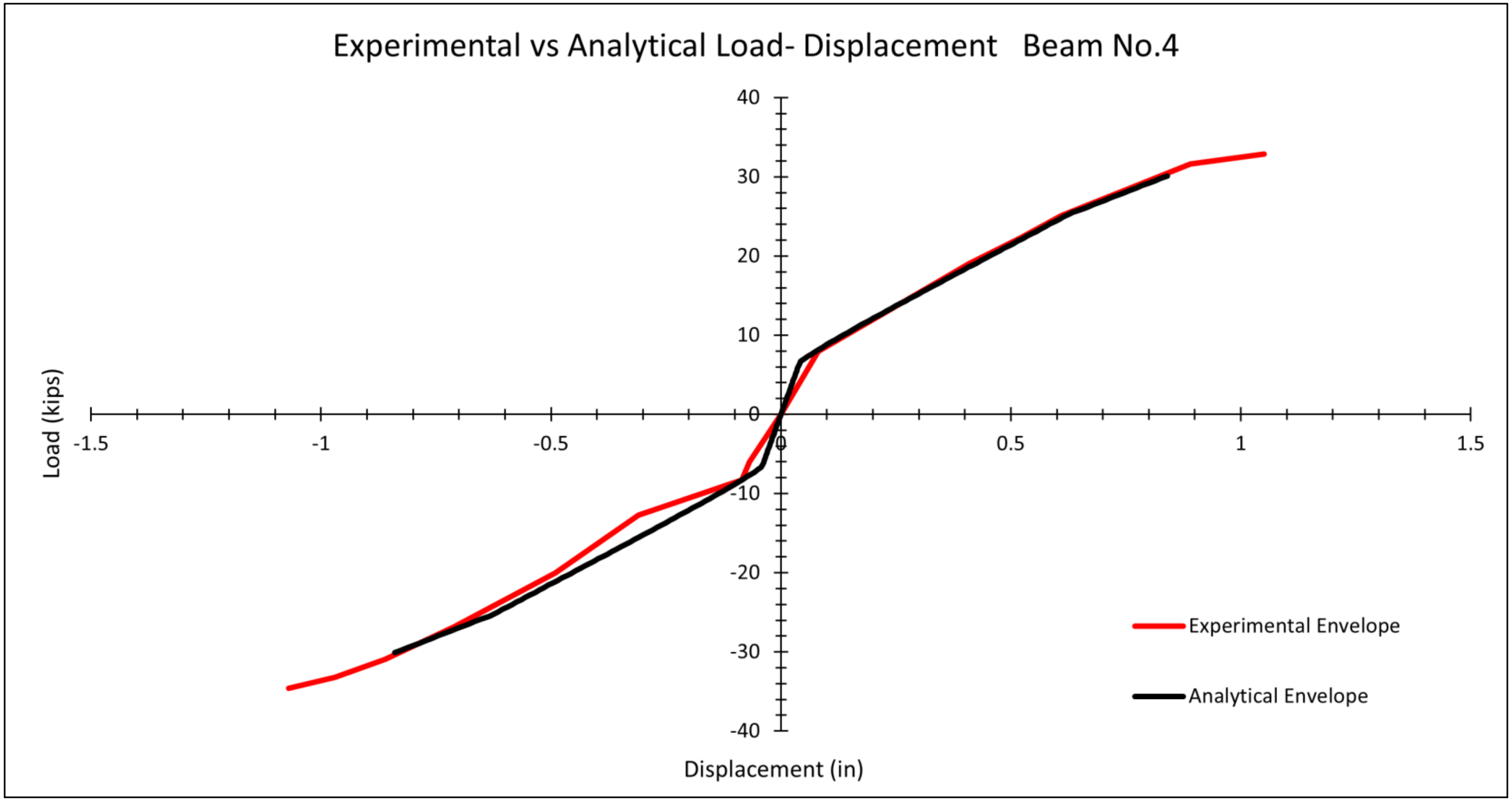
Analytical Model of Envelope Curve Cont.

- Experimental vs analytical model



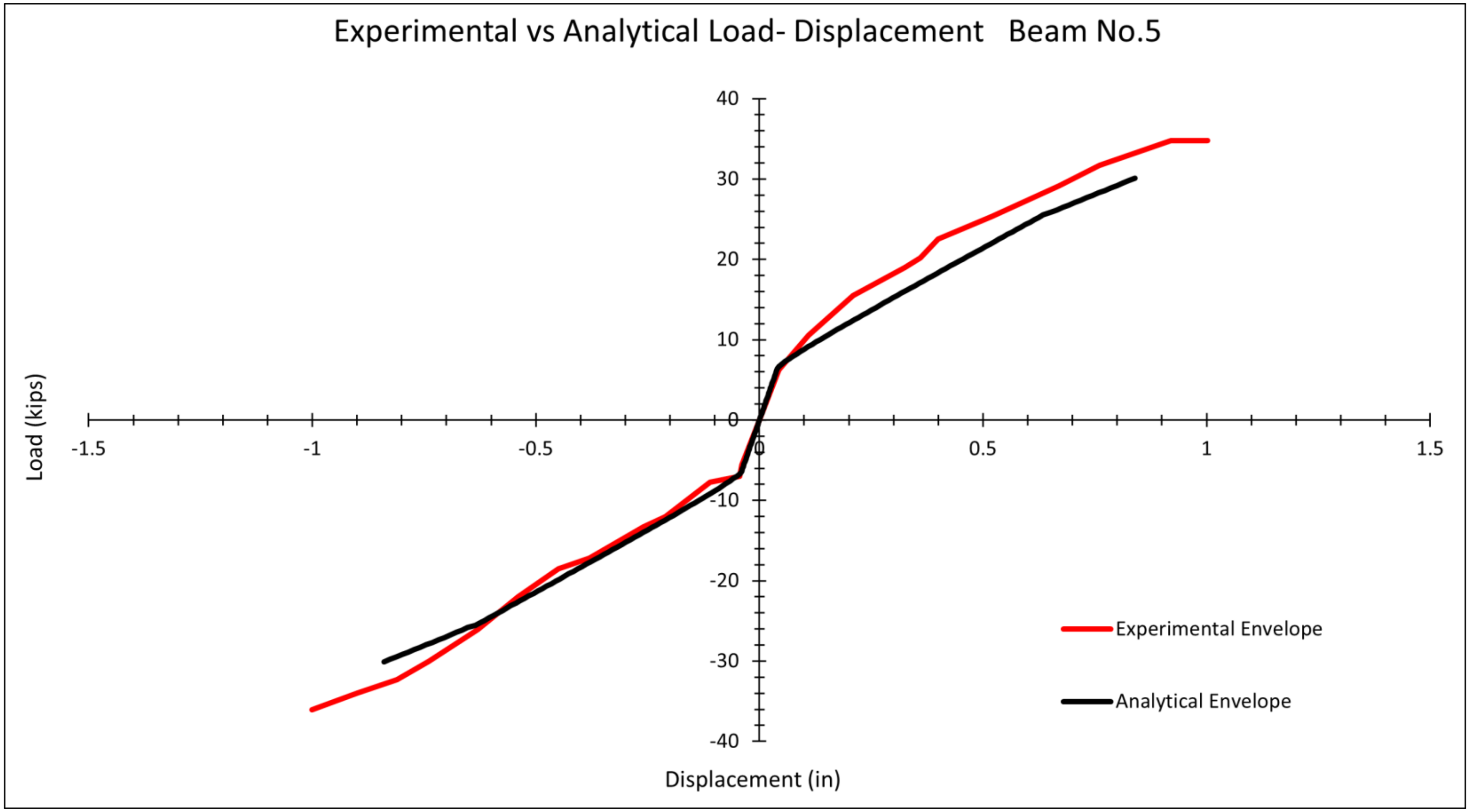
Analytical Model of Envelope Curve Cont.

- Experimental vs analytical model



Analytical Model of Envelope Curve Cont.

- Experimental vs analytical model



9. Conclusion

- Full-Scale RC beam strengthened with CFRP under reversed cyclic four-point bending is examined experimentally.
- Thin vs. thick CFRP sheets were used with and without anchors.
- Thin CFRP beams yielded higher ductility, more energy dissipation, and less seismic pinching compared to thick CFRP beams.
- The effect of anchors was limited due to the test setup forcing the loading points to act as equivalent anchors.
- A trilinear moment –curvature envelope curve was used to predict the load-deflection backbone response showing very good correspondence to test results.
- An extended testing protocol is planned to examine the cyclic response without restraining the CFRP from debonding at the loading points.

Thank You

Any Questions!